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64 slice MDCT generally underestimates coronary calcium scores as compared to EBT: A phantom study

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The objective of our study was the determination of the influence of the sequential and spiral acquisition modes on the concordance and deviation of the calcium score on 64-slice multi-detector computed tomography (MDCT) scanners in comparison to electron beam tomography (EBT) as the gold standard. Our methods and materials were an anthropomorphic cardio CT phantom with different calcium inserts scanned in sequential and spiral acquisition modes on three identical 64-slice MDCT scanners of manufacturer *A* and on three identical 64-slice MDCT scanners of manufacturer *B* and on an EBT system. Every scan was repeated 30 times with and 15 times without a small random variation in the phantom position for both sequential and spiral modes. Significant differences were observed between EBT and 64-slice MDCT data for all inserts, both acquisition modes, and both manufacturers of MDCT systems. High regression coefficients (0.90–0.98) were found between the EBT and 64-slice MDCT data for both scoring methods and both systems with high correlation coefficients ($R^2 > 0.94$). System *A* showed more significant differences between spiral and sequential mode than system *B*. Almost no differences were observed in scanners of the same manufacturer for the Agatston score and no differences for the Volume score. The deviations of the Agatston and Volume scores showed regression dependencies approximately equal to the square root of the absolute score. The Agatston and Volume scores obtained with 64-slice MDCT imaging are highly correlated with EBT-obtained scores but are significantly underestimated (−10% to −2%) for both sequential and spiral acquisition modes. System *B* is more independent of acquisition mode to calcium score than system *A*. The Volume score shows no intramanufacturer dependency and its use is advocated versus the Agatston score. Using the same cut points for MDCT-based calcium scores as for EBT-based calcium scores can result in classifying individuals into a too low risk category. System information and scanprotocol is therefore needed for every calcium score procedure to ensure a correct clinical interpretation of the obtained calcium score results.
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Key words: diagnostic techniques and procedures, tomography, x-ray computed, tomography, spiral and sequential computed, coronary arteriosclerosis, coronary calcium score, electron beam tomography, computed tomography

I. INTRODUCTION

The amount of coronary artery calcium (CAC) is known to be related to the risk of myocardial infarction and sudden death.[1] Electron beam tomography (EBT) is generally accepted as the gold standard for measuring CAC score in order to assess the extent and progression of atherosclerotic calcifications.[2–7] With the general availability of multidetector computed tomography (MDCT), this modality has become a commonly used tool for calcium score determination. Originally, the Agatston score (AS) was developed as a representative measure for the amount of coronary calcium.[8] More recently, the Volume score (VS) was proposed as a scoring method.[9] The normal progression of these CAC scores varies between 14%–27% and 33%–48% for patients with a relatively low and high CAC scores, respectively.[10] Because the variability on EBT is approximately 15%, and 8%–20% on spiral 16-slice MDCT[11] this jeopardizes the detection of CAC-score changes in patient monitoring programs. Therefore, in order to perform a clinical useful monitoring of CAC scores, the reproducibility of scores on one scanner has to be as high as possible and the variability of scores between two different scanners as low as possible.

Various studies have assessed the concordance of calcium scores between EBT and MDCT. Daniell *et al.* investigated the scores obtained with EBT and four-slice MDCT in 68 patients and reported similar interscan differences as reported previously for EBT and MDCT scanners individually.[12] Becker *et al.* showed a high agreement of coronary artery calcium measurement between EBT and four-slice MDCT in 100 patients, although the need for larger cohort studies, particularly in younger ages, was indicated.[13] In a cohort of 78 subjects, four-slice MDCT appeared to be comparable to EBT for coronary calcium screening, except for calcium scores less than 10.[14] Knez *et al.* demonstrated an excellent correlation between EBT and four-slice MDCT with a mean variability of 17% between both modalities.[15] Horiguchi *et al.*[16] reported that 16-slice MDCT yielded a low variability of CAC score and has advantages over EBT in monitoring the progression of atherosclerosis. Recently, an extensive overview of the scientific data for cardiac CT related to imaging of coronary artery disease and atherosclerosis was published by Budoff *et al.*[17]

In 2005 64-slice MDCT was introduced. With its increased temporal and spatial resolution compared to four- and 16-slice scanners, this modality is especially suited for noninvasive cardiologic examinations and has recently entered the field of calcium scoring. However, no comparative studies assessing differences between calcium scores obtained with EBT, and 64-slice MDCT have been available until now.

Sevrukov *et al.*[18] reported in 2004 on the basis of more than 2000 repeated EBT scans that the smallest statistically significant CAC change is ±4.930× square root of the AS and ±3.445× square root of the VS. Hokanson *et al.*[19] performed repeated EBT scans on more than 1000 participants and concluded that the square root of the VS stabilizes the deviation in interscan measurements. In order to test the concordance of CAC-score determination on 64-slice MDCT and the hypothesis that the deviation of the repeated calcium score measurements depends on the square root of the calcium score, we designed an experiment in which CAC scores were repeatedly determined from a cardiac CT phantom in spiral and sequential acquisition modes on both EBT and 64-slice MDCT with a small rotational and translational displacement between each consecutive measurement. The concordance of CAC-score determination was defined as the difference between the mean CAC score on 64-slice MDCT and on the gold standard EBT. The deviation was defined as the spread of the systems output by repeated measurements from the same input over a period of time.

The purpose of this study was to determine the influence of sequential and spiral acquisition mode on the concordance and deviation of CAC score on 64-slice MDCT scanners in comparison to EBT as the gold standard, and therefore to provide insight in the predictive value of the calcium score when determined on a 64-slice CT scanner.

II. MATERIALS AND METHODS

An anthropomorphic cardiac CT phantom (QRM, Möhrendorf, Germany) was imaged. The phantom consists of an artificial thorax with artificial lungs and a spine insert, surrounded by soft tissue equivalent material (Fig. 1). Centrally in the phantom, a cylindrical insert is present representing the heart. The cylinder contains nine inserts consisting of calcium hydroxyapatite with varying size and density. The specifications of the inserts are shown in Table I.

The phantom was scanned on six 64-slice MDCT scanners: Three identical scanners of manufacturer *A* and three identical scanners of manufacturer *B*. Imaging was performed with a sequential and a spiral acquisition protocol. Default scan protocol settings for calcium scoring were used as suggested by the manufacturer. Both protocols used 120 kV, 3.0 mm slice thickness and 320 mm field of view (FOV). Sequential scans were performed with 200 mA, spiral scans with 300 mA tube current. The rotation time of the scanners was 400 ms for one manufacturer and 370 ms for the other. Images were acquired at 75% of the cardiac cycle using a multisegment acquisition technique at a simulated heart rate of 71 beats per minute. To compare MDCT CAC scores with the generally accepted gold standard of EBT, the same phantom was scanned on an EBT system (e-Speed, GE-Imatron, South San Francisco, California). The default EBT sequential scan protocol was used: 130 kV, 50 mAs, 3.0 mm slice thickness and 100 ms acquisition time.

Two types of experiments were performed on all six scanners and on EBT, an experiment without position adjustment and an experiment with position adjustment. In order to assess the internal deviation and concordance of the scanners, in the first experiment the phantom was imaged 15 times with the same protocol without changing the position of the phantom in the scanner.

It is well known from other studies that the heart does not exhibit a perfectly repeated motion in every heart beat.[20,21] These random fluctuations in the heart position can cause image artifacts and blurring in the multisector reconstruction algorithm, which is generally used in patients with elevated heart rates.[22] In order to assess the deviation and concordance of CAC scoring in such a clinical situation, in the second experiment the phantom was scanned 30 times where the position of the phantom was changed by a small random translation equal to the average distal diameter of the coronary arteries of 2 mm and a random rotation of 2° between each consecutive scan. The translations of the phantom do not aim to resemble the heart motion but have been used to mimic these random fluctuations in the positioning of the human coronary artery in subsequent heart cycles. Both experiments were performed in sequential and spiral modes. Although the position of the object is not altered during the scan, as is the case in scanning the heart *in vivo*, this change in position between each scan will provide insight in the influence of the change in position on the CAC score.

The AS and VSs[23] were obtained from the reconstructed data in "Smartscore" running on an Advanced Workstation (GE, Chalfont St. Giles, UK). The manufacturer default set-

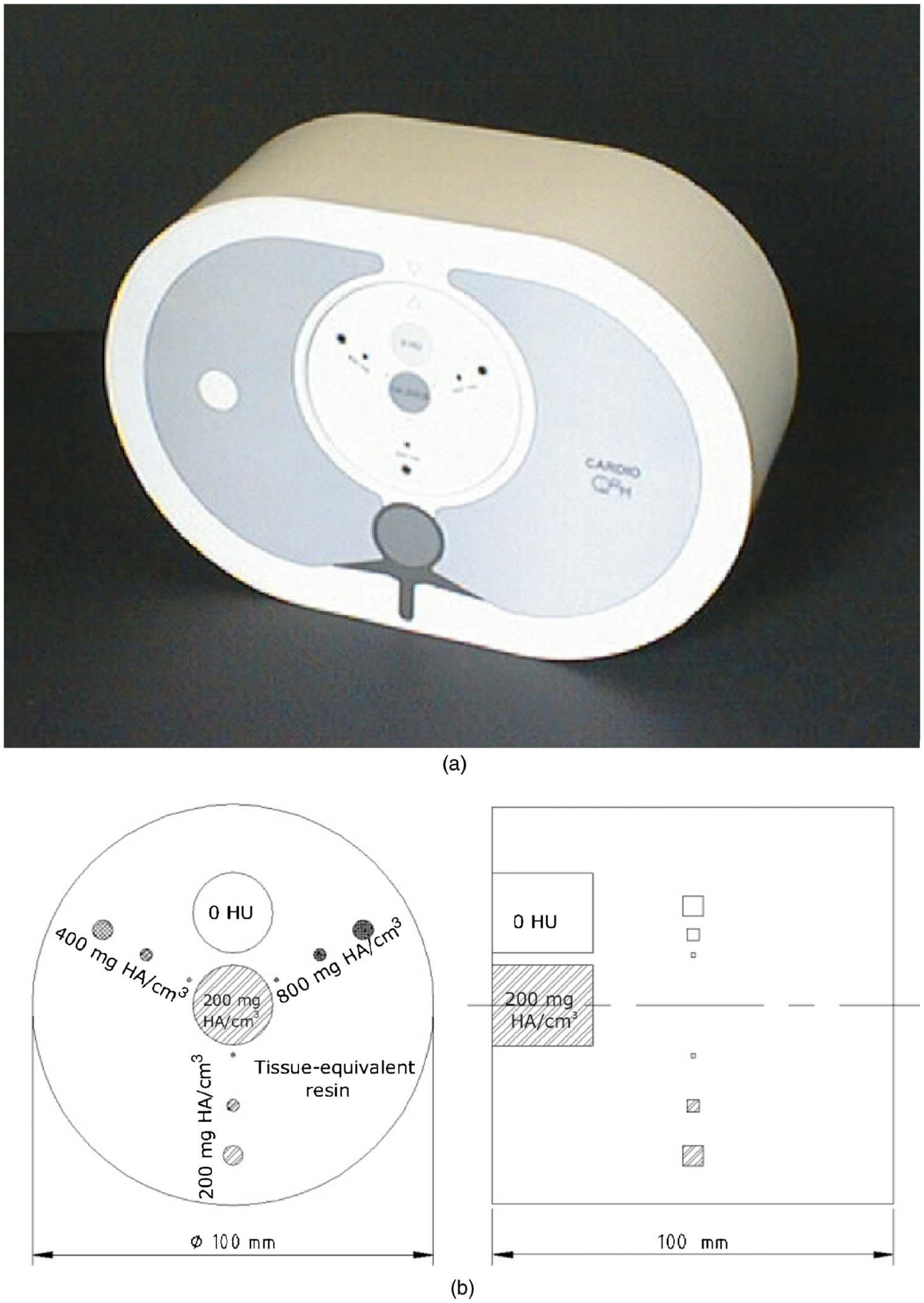

FIG. 1. Anthropomorphic cardio CT phantom.

ting for the calcium scoring algorithm were used, in which a calcified area in a slice was found if at least two connected pixels in the horizontal or vertical direction were detected with a pixel value above 130 HU ignoring connectivity between slices.[24] Each insert was labeled and scored individually.

On each MDCT scanner 90 scans were performed (30 scans with position adjustment and 15 scans without position adjustment in spiral and sequential mode) and 45 scans on the EBT scanner (only sequential mode). The CAC score of seven inserts of the cardiac phantom was determined (see Section III), which yields $7 \times 90 = 630$ data points per MDCT scanner and $7 \times 45 = 315$ data points for the EBT scanner.

TABLE I. Properties of the seven artificial calcifications used in the anthropomorphic cardiac CT phantom.

Calcification	HA Density (mg/cm^3)	Length (mm)	Diameter (mm)	Area (mm^2)	Volume (mm^3)
1	800	5.0	5.0	19.6	98.2
2	800	3.0	3.0	7.1	21.2
3	800	1.0	1.0	0.8	0.8
4	400	5.0	5.0	19.6	98.2
5	400	3.0	3.0	7.1	21.2
6	200	5.0	5.0	19.6	98.2
7	200	3.0	3.0	7.1	21.2
8	400	1.0	1.0	0.8	0.8
9	200	1.0	1.0	0.8	0.8

TABLE II. Average Agatston and Volume scores with standard deviation of the seven artificial calcifications measured on EBT, System *A*, and System *B* in sequential and spiral modes. Significant *p* values of the paired t-test between the EBT and CT results are displayed in italic.

	EBT	System *A*				System *B*			
Calcium cylinder diameter and density	Sequential Mode	Sequential Mode	*p* Value	Spiral Mode	*p* Value	Sequential Mode	*p* Value	Spiral Mode	*p* Value
Agatston score									
1 mm diameter									
800	0.6±0.6	0.6±0.6	0.4	0.2±0.4	0.07	0.6±0.6	0.65	0.6±0.5	0.48
3 mm diameter									
200	12±4	12±4	0.76	9±4	*<.01*	12±4	0.26	12±4	0.92
400	44±3	38±5	*<.01*	33±5	*<.01*	43±5	0.13	43±4	0.08
800	79±14	73±13	*<.01*	76±11	0.08	78±15	0.38	77±14	0.35
5 mm diameter									
200	72±11	58±12	*<.01*	61±12	*<.01*	83±13	*<.01*	80±12	*<.01*
400	195±14	181±17	*<.01*	179±14	*<.01*	197±17	0.26	198±15	0.13
800	287±27	264±26	*<.01*	272±28	*<.01*	282±27	0.19	270±24	*<.01*
Volume score									
1 mm diameter									
800	1.6±1.8	1.7±1.8	0.24	0.4±1.0	*0.03*	1.4±1.6	0.87	1.5±1.5	0.83
3 mm diameter									
200	21±3	20±3	*<.01*	17±3	*<.01*	21±3	0.51	21±3	0.92
400	45±7	38±7	*<.01*	39±7	*<.01*	43±7	0.06	41±7	*<.01*
800	66±7	60±9	*<.01*	64±5	0.09	63±11	*0.02*	63±10	*0.03*
5 mm diameter									
200	109±11	96±17	*<.01*	99±13	*<.01*	112±15	0.21	115±13	*<.01*
400	174±18	160±14	*<.01*	162±17	*<.01*	168±14	*0.01*	168±14	*0.01*
800	233±21	212±25	*<.01*	223±24	*<.01*	223±26	*0.01*	212±27	*<.01*

The scored data were statistically analyzed using SPSS for Windows 12.0 (SPSS Inc, Chicago, IL). Data were checked for normality and are presented as mean ± standard deviation. The statistical differences between EBT and 64-slice MDCT CAC scores were analyzed using a paired Student's *t*-test. A significance level of 5% was used for each analysis. The correlation between EBT and 64-slice MDCT CAC scores was analyzed using a least square fit of a linear regression model in Microsoft Excel (Microsoft Corp, Redmond, Washington). A comparison was made between CAC scores obtained on systems *A* and *B* in spiral and sequential modes and data were statistically tested using a paired Student's *t*-test. An intrasystem comparison between CAC scores obtained in spiral and sequential mode was made and statistically tested using a paired Student's *t*-test. The average deviation in percentage of the total CAC score of all inserts on EBT, and for both acquisition modes on both 64-slice MDCT systems A and B was calculated for both experiments for Agatston and Volume scores. Finally, we assessed how the average deviation of the absolute CAC score (ΔS) depends on the absolute score (S) of both scoring methods by plotting ΔS versus S, and fitting to $\Delta S = aS^b$ using Microsoft Excel.

III. RESULTS

III.A. CAC scores on EBT compared to MDCT

In this study the AS and VS were measured of the three 3 mm inserts and the three 5 mm inserts each with a calcium density of 200, 400, and 800 mg/cm^3 (inserts 1 to 6). The 1 mm inserts with 200 and 400 mg/cm^3 calcium density (inserts 8 and 9) could not be identified on the scan images and were therefore omitted from the results. The score of the 1 mm cylinder with the highest density (insert 3800 mg/cm^3) was included only when it was detected in more than 50% of the 15 experiments without position adjustment or 50% of the 30 experiments with position adjustment. The results of the CAC-score determination of the experiment with position adjustment are shown in Table II. A significant difference ($p < 0.03$) was observed between the EBT data and 64-slice MDCT for most of the inserts, both acquisition modes and both systems *A* and *B*. Fewer significant differences were, however, found for system *B*, especially for the AS.

The individual AS's of the experiment with position adjustment on 64-slice MDCT were plotted versus the EBT resulting in a correlation analysis for sequential and spiral mode CT (Fig. 2). In Fig. 3 the VSs obtained by sequential and spiral mode CT versus EBT are plotted. The results of

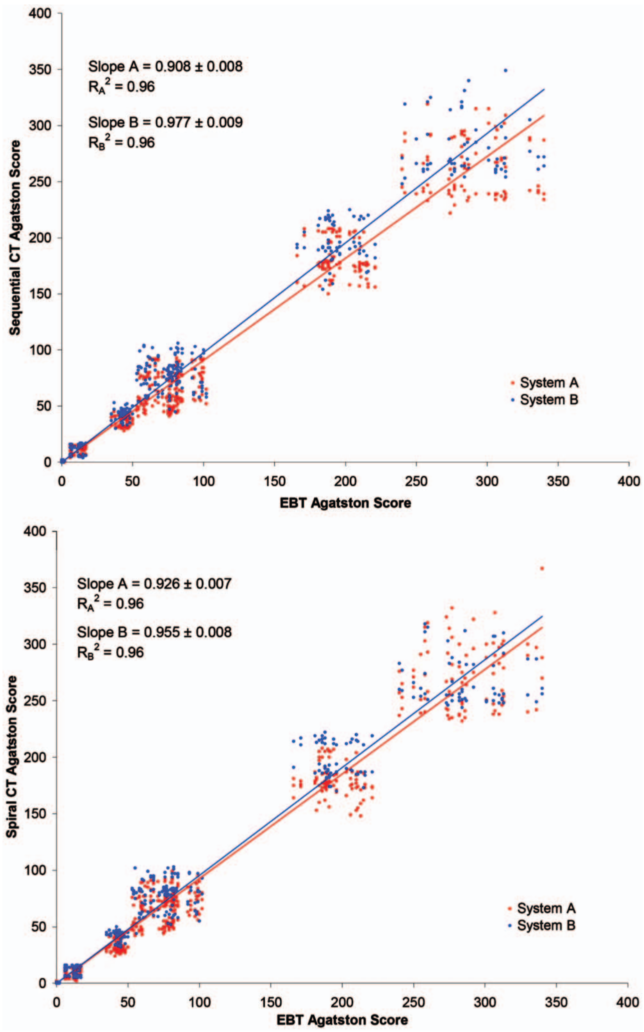

FIG. 2. Correlation of Agatston score between CT and EBT in (a) sequential and (b) spiral modes for system A (red) and system B (blue). The linear regression coefficient and correlation coefficient R^2 are given.

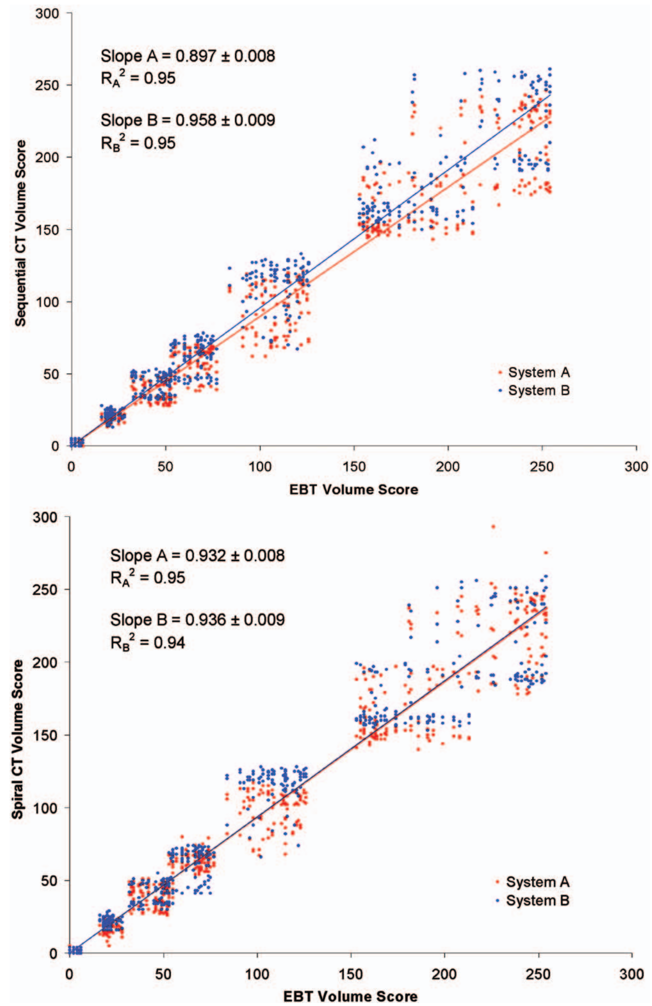

FIG. 3. Correlation of Volume score between CT and EBT in (a) sequential and (b) spiral modes for system A (red) and system B (blue). The linear regression coefficient and correlation coefficient R^2 are given.

the regression analyses are shown in the figures. A high correlation coefficient ($R^2 > 0.94$) between the EBT and 64-slice MDCT data was observed for both scoring methods and both systems (A and B). In sequential mode, regression coefficients ranged from 0.897 for VS on system A to 0.977 for AS on system B. The average regression coefficient of system B (0.957) was closer to 1.0 than the average regression coefficient of system A (0.916). The regression coefficient of the VS on system B was smaller than the regression coefficient of the AS, whereas system A did not show a significant deviation in regression coefficient.

III.B. Sequential mode versus spiral acquisition mode, an intrasystem comparison

In Table III a statistical analysis is shown of the CAC scores obtained in sequential acquisition mode versus a spiral acquisition mode on the three identical 64-slice MDCT scanners A1–A3 and the three identical 64-slice MDCT scanners B1–B3 for AS and VS. From an analysis of the p-values of the paired Student's t-tests we found that the number of significantly different CAC scores between sequential and spiral acquisition modes is considerably higher for system A than for system B. The AS and VS on system A showed a significant difference in 11/21 (52%) and 7/21 (33%) cases, respectively, versus 1/21 (5%) and 2/21 (10%) cases for system B.

From an analysis of the p-values of the paired Student's t-tests between the CAC scores obtained on scanners of the same manufacturer (not shown), we found that only in 1/6 cases (17%) system A showed a significant difference between scanner A1 and A2 for AS in spiral mode, whereas in 2/6 cases (33%) system B showed a significant difference between scanner B3 and B1/B2 for AS in sequential mode. No significant differences were observed for VS on both systems and for both acquisition modes.

III.C. Comparison of CAC score deviations on EBT and MDCT

In Figures 4(a) and 4(b) the results are shown of the analysis of the average deviation in percentage of the total CAC score of all inserts on EBT, and for both acquisition

TABLE III. Comparison of Agatston and Volume scores obtained in spiral vs sequential mode on System *A* and System *B*. Significant different *p* values between spiral and sequential scores are displayed in italic.

Calcium cylinder diameter and density (mg/cm^3)	*p* Values Scanners System *A*			*p* Values Scanners System *B*		
	A_1	A_2	A_3	B_1	B_2	B_3
Agatston score						
1 mm diameter						
800	0.2	*<.01*	*<.01*	0.23	0.57	0.28
3 mm diameter						
200	*<.01*	*<.01*	*0.01*	0.28	0.42	0.77
400	*0.02*	*<.01*	*<.01*	0.52	0.09	0.47
800	0.42	*0.04*	0.8	0.61	0.59	0.27
5 mm diameter						
200	0.2	*0.04*	0.84	0.21	0.97	0.09
400	0.32	0.24	0.88	0.96	0.33	0.71
800	0.55	*0.03*	0.11	0.15	*0.04*	0.06
Volume score						
1 mm diameter						
800	0.13	*<.01*	*<.01*	0.93	0.78	0.34
3 mm diameter						
200	*<.01*	*<.01*	*<.01*	0.14	0.24	0.07
400	0.33	0.97	0.22	*0.04*	0.34	0.60
800	0.09	*<.01*	0.31	0.91	0.33	0.51
5 mm diameter						
200	0.10	0.36	0.86	0.29	*<.01*	0.52
400	0.30	0.79	0.97	0.58	0.66	0.77
800	0.68	*<.01*	0.06	0.32	0.12	0.10

modes on both systems *A* and *B* for both experiments for AS and VS. The deviation of the EBT Agatston score of the experiment without position adjustment was 2.1%, whereas the deviation of the experiment with position adjustment was 5.9%. This increase in deviation was observed for all scanners and acquisition modes. The AS deviation of the experiments with position adjustment ranged from 5.4% for system *A* to 3.9% for system *B*. The VS deviation for system *A* showed similar results as the AS deviation, whereas for system *B* the VS showed increased deviation with respect to the AS.

Finally, in Figs. 5(a) and 5(b) the deviation in percentage of the AS and VS of all inserts is plotted. From a linear fit of the data in this figure to $\Delta S = aS^b$ a strong dependence of the deviation on absolute score was deduced: $a=0.85\pm0.05$, $b=0.58\pm0.01$ for AS and $a=1.04\pm0.10$, $b=0.53\pm0.02$ for VS.

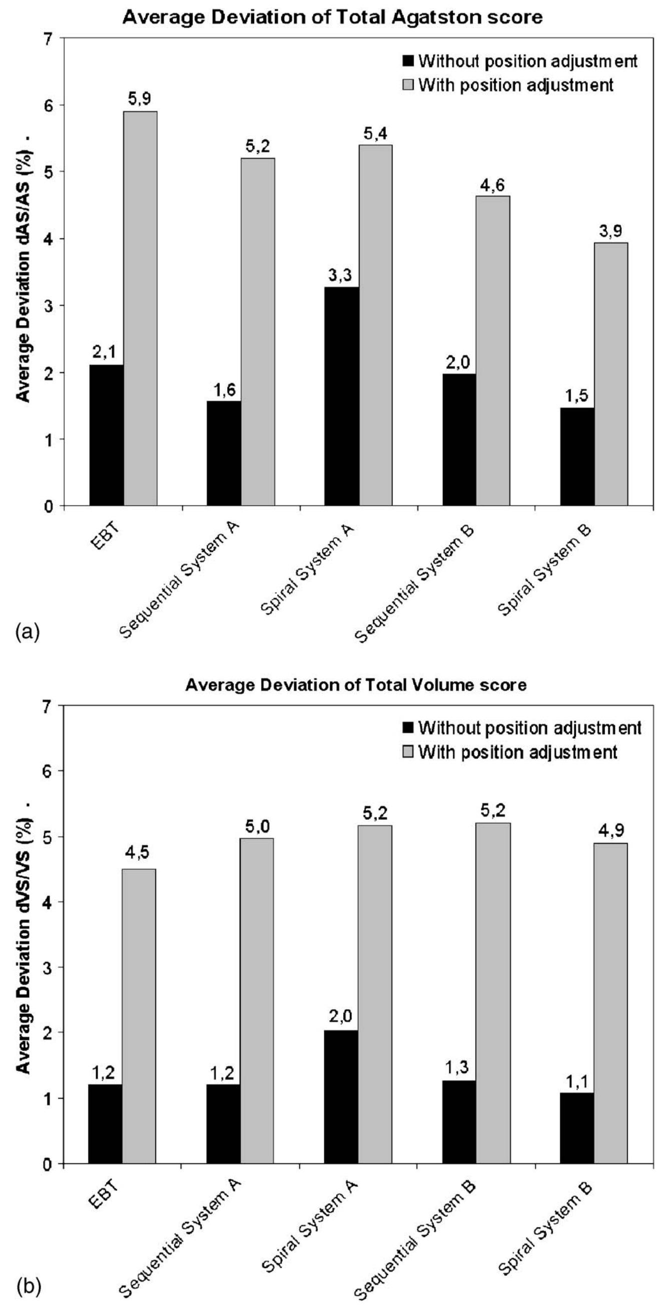

FIG. 4. Average deviation in percentage of (a) the total Agatston score $\Delta AS/AS$ and (b) the total Volume score $\Delta VS/VS$ of all inserts obtained in the experiment without position adjustment compared with the experiment with position adjustment for EBT and systems *A* and *B* in sequential and spiral modes.

IV. DISCUSSION

We determined the deviation and concordance of AS and VS of seven artificial calcium inserts in a cardiac phantom on a total of six 64-slice MDCT systems of two manufacturers for sequential and spiral acquisition modes and compared these data to EBT as the gold standard. A significant difference in the CAC scores was found between EBT and 64-slice MDCT for all artificial calcifications on both systems *A* and *B* for both acquisition modes. Fewer significant deviations were found for system *B* for both scoring methods and acquisition modes. Both systems *A* and *B* showed high regression coefficients of CAC score on 64-slice MDCT versus EBT (0.897 to 0.977) with high correlation coefficients ($R^2 > 0.94$). System *B* showed higher regression coefficients for both scoring methods and acquisition modes. Significant differences in concordance between spiral and sequential mode were observed for both systems, with more significant differences for system *A* for both scoring methods compared to system *B*. In some cases significant differences in concor-

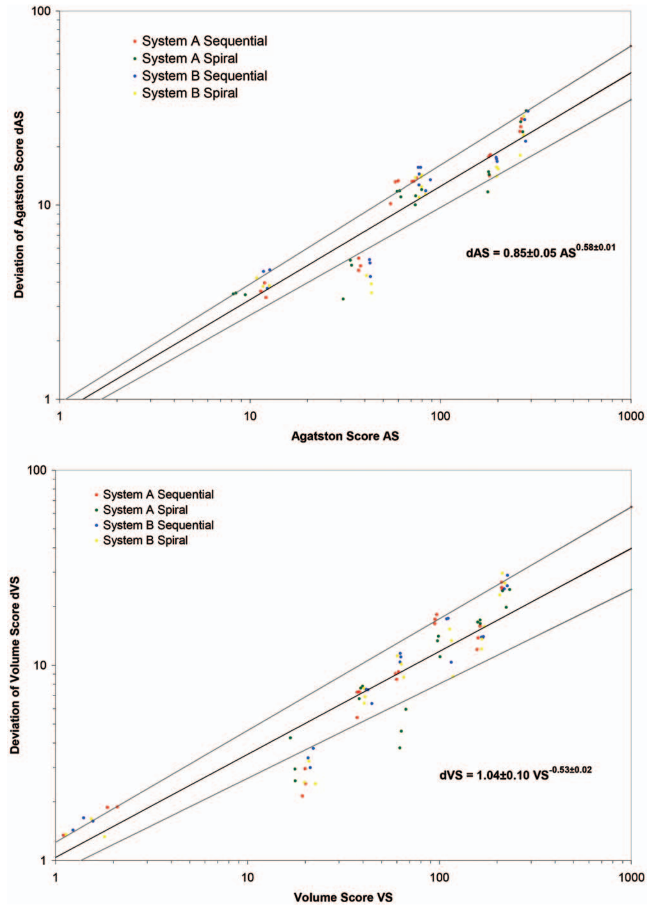

FIG. 5. Deviation of (a) Agatston score ΔAS and (b) Volume score ΔVS as a function of absolute score of the individual seven inserts plotted on a double log scale. The CAC scores of systems *A* and *B* in sequential and spiral modes are fitted to an exponential trend line. The results of the fit and the 95% confidence bands are shown.

dance were found in CAC-score determination for scanners of the same manufacturer. The deviation of the CAC score was determined and an approximately square root dependence of the deviation on absolute score was found. The VS showed no significant intramanufacturer differences in contrast to AS.

IV.A. CAC scores on EBT compared with MDCT

The CAC scores obtained from the phantom used in this study (Table II) are comparable to the results reported previously by Vliegenthart *et al.* using an EBT system.[25] In 2000, single slice spiral CT was compared to EBT by Carr *et al.* and a high correlation was found with scores obtained with EBT.[26] A study in which a heart phantom was imaged by EBT and four-slice MDCT in order to compare calcium scores was published by Ulzheimer *et al.* in 2003.[27] Although a high correlation was found, especially low scores (<50) seemed to be underestimated with MDCT compared to EBT. This is confirmed by our measurements in which system *A* shows a significant underestimation. Significant differences between EBT CAC scores have also been reported in patient groups by Golding *et al.*[28] using single slice helical CT and Becker *et al.*[13] using four-slice MDCT. Recently, Horiguchi[11] reported an underestimation of VS in 79% of the scans on spiral 16-slice MDCT.

Several other studies have addressed the correlation between CAC scores on EBT and MDCT. Becker *et al.*[29] reported a regression coefficient of 0.976 comparing single slice CT and EBT. Daniell *et al.*[12] reported a regression coefficient of 1.0959 and 0.9947 for AS and VS, respectively, comparing four-slice MDCT at 2.5 mm slices and EBT at 3 mm slices both in sequential mode. We obtained regression coefficients which were 10%–17% smaller for system *A* and 4%–11% smaller for system *B* depending on the acquisition mode. Ulzheimer *et al.*[27] reported values of 1.0708 and 1.0165 for the AS and the sequential and the spiral modes, respectively, on four-slice MDCT. These values are 9%–15% larger than we found for system *A* and 6%–9% larger for system *B*. This increase in regression coefficient from sequential to spiral mode was also observed for system *A*, whereas system *B* showed a decrease of 2%. Carr *et al.*[26] reported a regression coefficient of 0.96 acquired at 3 mm slices on four-slice MDCT, which corresponds well with our results. Finally, Knez *et al.*[15] reported a regression coefficient of 1.0211 for VS on sequential four-slice MDCT versus EBT, which is approximately 14% higher than for system *A* and 6% higher than for system *B*, again by using 2.5 mm slices. A decrease of CAC scores with a decrease of slice thickness has also been reported by others and is caused by the partial volume effect.[23,25] A high regression coefficient of 0.977 was also reported by Horiguchi *et al.*[30] comparing AS's on four-slice MDCT and EBT. This value is increased to 0.988 using a multisector reconstruction algorithm for improved temporal resolution. The regression coefficients we obtained correspond well with the previous reported values for single slice, four-slice, and 16-slice MDCT in comparison to EBT.

IV.B. Sequential mode versus spiral acquisition mode, an intrasystem comparison

Horiguchi *et al.* reported that spiral protocols on 16-slice MDCT yielded significantly lower score values than sequential protocols for AS's between approximately 150 and 250 using a cardiac phantom.[10] In our study, this was observed especially for system *A*, whereas system B did not show any significant differences between sequential and spiral protocols except for AS of the 5 mm 800 mg/cm^3 insert and the VS's of the 3 mm 400 mg/cm^3 and 5 mm 200 mg/cm^3 insert.

Kopp *et al.*[37] have shown that the reproducibility and accuracy of coronary arterial calcium determination with 4-MDCT is improved by using a spiral protocol versus a sequential protocol. Their study showed that nonoverlapping sequential scanning is the most important contributor to interexamination variability of AS and VS calcium scores because of partial volume errors in plaque registration. The use of thin slice retrospective spiral ECG gated has been advocated for coronary calcium assessment in 16-MDCT[10] and recently in 64-MDCT also.[31] For spiral CT, however, the slice sensitivity profile is broadened by the movement of the table[32] which may lead to an underestimation of contrast of especially low density calcifications.[10,11] We expect that due to the spiral scanning protocol the density profile of the calcification is broadened, which may lead to an underestimation of the calcium score compared to the calcium score obtained in a sequential scanning protocol with a thinner slice sensitivity profile. This disadvantage can be overcome by using both thin-slice images and overlapping image reconstruction.[10,11]

IV.C. Comparison of CAC score deviations on EBT and MDCT

From Fig. 4 we derived that spiral mode results in lower average deviation values in comparison to sequential mode, which is in good agreement with the results of Horiguchi *et al.*[10] However, EBT deviation measured in our study was not higher than for spiral CT as reported by Horiguchi for the 100–400 score range. Diverging results can be explained by the phantom type. Horiguchi used a dynamic cardiac phantom, simulating heart cycle, whereas a static phantom was used in our study. Recently, an error of measurement of 5% on EBT and 2%–6% on spiral CT was reported using an artificial coronary artery.[11] These measurement errors correspond well with our results.

We found that the deviation of AS and VS on system A and B for both acquisition modes depends approximately on the square root of the absolute score (Fig. 5). This result is in good agreement with the analysis of Sevrukov *et al.*,[18] who concluded that the difference D between the average A of repeated CAC measurements on EBT is given by $D = 2.007\sqrt{A}$. Hokanson *et al.*[19] found that the square root of the CAC score stabilizes interscan variability across the range of VS's on EBT of more than 1000 patients.

IV.D. Limitations

Images on three scanners of each system (A and B) were made, resulting in three times as many data points for each system than for EBT on which both experiments were performed only once. It would have been more systematic if the experiments were performed on three EBT systems also. However, since EBT is generally accepted as the gold standard for CAC score,[17] we do not expect that addition of two more *e*-Speed EBT scanners in our experimental setup would have changed the outcome of our analysis significantly.

The effect of cardiac motion on the outcome of CAC scores fell out of the scope of the present work. It has, however, been shown on four-slice and 16-slice MDCT that temporal resolution and the patient's heart rate have a strong influence on CAC score.[27,33,34] It can be expected that calcium scores show larger differences in patients. We, therefore, expect that the current results for deviation with our static phantom will set a lower limit if motion is included. Research assessing calcium score differences between 64-slice MDCT and EBT obtained from dynamic cardiac heart phantoms is currently in progress. In this study we investigated the concordance and deviation of two CAC scoring methods: AS and VS. A third scoring method, equivalent mass (EM) was, however, not assessed.[35,36] Because there is evidence that EM exhibits a lower variability than the other scoring methods[37] the assessment of equivalent mass is included in the current research.

The artificial coronary calcifications mimicked by the inserts in our anthropomorphic cardiac phantom are, in contrast to the *in vivo* situation, relatively uniform in Hounsfield units (HU) value and density. Since the CAC scores and especially the AS depend on the measured CAC density, it is expected that with a relatively strong variation of HU values within the coronary plaque the resulting deviation of the CAC scores will increase further.

IV.E. Clinical implications

This is the first study to assess possible intrasystem differences between scanners of the same manufacturer, installed on different sites. Our study shows that no significant differences exist when calcium scores are compared between different scanners of the same manufacturer. The concordance and deviation of CAC score on MDCT can be further increased by using optimal spatial and temporal resolution. Although thin slice protocols are generally advocated, these techniques are not commonly used in CAC score protocols because of increased patient dose.

Although thin slice spiral scanning has the advantage of high resolution and reproducibility, it results in an increase of radiation exposure. Different approaches have been examined to decrease the radiation dose: ECG-modulation,[38] automated attenuation-based tube current adaptation[39] and body-weight-adapted examination protocols,[40] which may lead to dose reductions of up to 46%. However, as been shown recently by Van der Molen *et al.* a spiral acquisition mode may lead to a dose increase of up to 17% with respect to a sequential acquisition mode due to overranging.[41] For the spiral mode to be established as a screening tool for the determination of coronary artery calcification, this effect has to be considered further.

Increasingly, calcium scoring is being used as a method to evaluate the presence and extent of coronary atherosclerosis, as a marker of cardiovascular risk, in asymptomatic individuals and in patients with a low suspicion of coronary disease. A commonly used categorization uses calcium score cut points of 0, 100, and 400 to stratify individuals.[42] The cut points have been found to be related to the risk of significant coronary artery disease. Further diagnostic and therapeutic management depends on the calcium score category in which the individual is placed. An accurate measurement of the calcium score and correct cardiovascular risk classification according to the calcium score is therefore of high importance. The results of our study suggest that there is considerable variability in calcium scores for different CT systems and that MDCT usually results in an underestimation of the calcium score. For example, a subject with a calcium score of above 400 on an EBT scan, generally indicating a need for further diagnostic testing, may well have a calcium score far below 400 on a MDCT scan and will be missed out on the needed diagnostic exams. In the worst case scenario, a patient with a VS of 400 on EBT will exhibit an underestimation of −10% on system *A* resulting in an apparent VS of 360. Because there is a 2.5% probability that this mean value is underestimated by two standard deviations in an actual measurement, this may result in a further reduction of the apparent VS to 322. Thus, using the same cut points for MDCT-based calcium scores can result in classifying individuals into a risk category that is too low. In addition, an accurate determination of the calcium score is very important when repeated measurements of coronary calcification are being performed, to follow the development of atherosclerosis, with or without antiatherosclerotic therapy. With every calcium scoring study, it is highly recommended to document the system manufacturer, scan protocol, and scoring method. Also, the component of systematic measurement error may allow for adjustment of the resulting calcium scores per system, so that categorization can be made more comparable to EBT, the system that the categorization is based on, and hence more accurate.

V. CONCLUSION

Coronary calcium scores measured by 64-slice MDCT scanners of different manufacturers differ in comparison with EBT results. While system *A* shows a systematic significant underestimation in most cases, system *B* does not show these significant differences compared to EBT. Although scores obtained on system *B* in spiral mode do not differ significantly from scores obtained in sequential mode in most cases, system *A* shows significant differences between sequential and spiral mode. These results stress the need for documentation of the scanner manufacturer and the scan protocol when using the CAC score as a measure for risk of myocardial infarction and sudden death. Variability in calcium scores is considerable for MDCT and EBT, especially in the low calcium score range. As a consequence of the different scoring results between MDCT and EBT, MDCT scanners of different manufacturers, different acquisition modes, and between scoring protocols, patient calcium scoring results need to be interpreted in the light of system-specific calcium score standards in order to prevent an underestimation of patient risk. Follow-up patient studies should preferably be performed on the same scanner with the same protocol. Since VS shows no intramanufacturer dependency, its use is advocated versus AS.

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